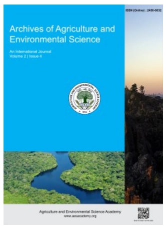
Archives of Agriculture and Environmental Science 9(4): 748-754 (2024)
https://doi.org/10.26832/24566632.2024.0904016

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



ORIGINAL RESEARCH ARTICLE

CrossMark

Effect of micronutrients on the growth and yield parameter of spring maize in Gauradaha, Nepal

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ARTICLE HISTORY

Received: 22 September 2024
Revised received: 21 November 2024
Accepted: 30 November 2024

Keywords

Growth
Micronutrients
TX-369
Yield
Zea mays

ABSTRACT

Micronutrients, required in trace amounts, are crucial for crop growth and metabolic activities. Maize is susceptible to micronutrient deficiencies and exhibits hidden hunger symptoms when lacking essential nutrients. This study, conducted at Gauradaha Agriculture Campus, Jhapa, from January to June 2023, aimed to assess the impact of zinc (Zn), boron (B), and sulfur (S) on maize growth and yield. A single-factorial randomized complete block design (RCBD) was used with seven treatments and three replications. Results revealed that the combined application of micronutrients with the recommended dose of NPK significantly enhanced maize growth and yield parameters. The T6 treatment (Zn 10 kg/ha + B 6 kg/ha + S 7 kg/ha with recommended NPK) produced the highest values for key growth indicators: leaf area, ear length (19.56 cm), ear diameter (6.24 cm), kernel rows per ear (15.72), grains per row (44.25), ear weight (17.65 tons/ha), biological yield (34.80 tons/ha), grain yield (12.68 tons/ha), and stover yield (3.39 tons/ha). Additionally, T4 (S 40 kg/ha with NPK) resulted in the highest test weight (438.33 g). Micronutrient application did not significantly affect plant height or the number of leaves. The study concludes that applying 10 kg/ha of Zn, 6 kg/ha of B, and 7 kg/ha of S with NPK significantly improves maize yield, demonstrating suitability for the local soil conditions and offering a practical approach to mitigate hidden hunger in maize.

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Citation of this article: Aryal, D., Magar, R. G., Tamang, A., Chaudhary, P., & Tamang, R. K. (2024). Effect of micronutrients on the growth and yield parameter of spring maize in Gauradaha, Nepal. *Archives of Agriculture and Environmental Science*, 9(4), 748-754, https://dx.doi.org/10.26832/24566632.2024.0904016

INTRODUCTION

Maize (*Zea mays* L.) is an annual crop and an essential staple crop, ranks third globally in production after wheat and rice (Bhaumik *et al*., 2023). Maize is a versatile crop grown in various agro-climatic zones, from 58°N to 40°S latitudes, at elevations from sea level to over 3000 m, with annual rainfall between 250 mm and 5000 mm. Its growing season ranges from three to thirteen months (Behera *et al*., 2022). It is commonly called the "queen of cereals" because it has the highest yield potential among cereal crops. As a C4 plant, it efficiently utilizes solar energy, even under high radiation intensities (Borase *et al*., 2018). Maize is the primary and essential food crop in Nepal's hills and mountains (Thapa, 2021). In Nepal, it ranks as the second most widely grown crop after rice (Kandel, 2021). In Nepal, maize yields have improved marginally from 2,997,733 to 3,106,397 metric tons between 2021 and 2022 (MoALD, 2022), yet productivity remains constrained partly due to hidden hunger micronutrient deficiencies that compromise crop potential without obvious symptoms. Micronutrients are essential elements required for the optimal growth and development of plants. They are needed in small quantities, often measured in grams per hectare or milligrams per kilogram of soil or biomass (Alloway, 2013). To enhance crop yield and quality, applying micronutrients, particularly zinc, boron, and sulfur, in maize fields is advisable to achieve optimal results (Chopde *et al*., 2015).

Micronutrients are essential for plant metabolic processes, including the formation of cell walls in leaves, which are integral to critical functions such as photosynthesis and transpiration (Kumar, 2014; Tripathi, 2015). Sulfur is the fourth most important nutrient after nitrogen, phosphorus, and potassium, playing a vital role in numerous plant metabolic processes (Kumari *et al*., 2022). Several sulfur-containing substances fulfill protective functions in cellular adaptation, responses to abiotic stress, and the adaptation of plants to harsh conditions (Khan *et al*., 2014). External sulfur supplementation assists plants in surviving stressful conditions by sustaining their typical metabolic processes and enhancing crop yields. Additionally, sulfur shields plants from manganese toxicity by bolstering antioxidant defenses and facilitating the translocation of manganese from roots to various plant tissues (Venkateswarlu *et al*., 2012). Boron is indispensable for synthesizing and maintaining cellular structures and supporting overall carbohydrate metabolism and transport systems within the plant (Banerjee *et al*., 2021). Using boron (B) substantially enhances crop yield and nutrient uptake while mitigating the adverse effects of abiotic stress (Kumari *et al*., 2022). It enhances the efficiency of photosynthesis, hormone production, sugar transportation, lipid metabolism, flower retention, pollen development, seed germination, and overall seed yield in agricultural plants. Consequently, it boosts their resilience to drought stress (Michael & Krishnaswamy, 2012). Zinc (Zn) supplementation enhances the plant's defense against heat stress by preserving membrane integrity within its system (Bashir *et al*., 2016). It plays a significant role in alleviating chilling stress in plants (Xie *et al*., 2018). Zinc is crucial for preserving the structural integrity of proteins, membrane lipids, various cellular components, and DNA. Additionally, it facilitates ion transport within plants (Nadeem & Farooq, 2019). However, this study aims to assess the effects of Zn, B, and S supplementation on the growth and yield of spring maize, variety TX-369. By evaluating these nutrients in combination with standard NPK fertilization, this research addresses a critical knowledge gap and offers insights for enhancing local maize production, contributing to regional food security and sustainable agricultural practices.

MATERIALS AND METHODS

Experimental design and treatment details

The research was conducted from January to June 2023 at the agronomy research field of Gauradaha Agriculture Campus, Institute of Agriculture and Animal Science (IAAS), Gauradaha-02, Jhapa, Nepal (26°33'41.0"N, 87°43'13.6"E) at an altitude of 182 m. A Randomized Complete Block Design (RCBD) with seven treatments and three replications was used. Each treatment plot measured 6 m^2 (3 m × 2 m), covering a total research area of 273 m^2. Spacing between replications was 1 m, between treatments was 0.5 m, row-to-row spacing was 70 cm, and plant-to-plant spacing was 25 cm.

The seven treatments included:

T1: RDF of NPK (150:60:40 kg/ha) + Sulfur 20 kg/ha

T2: RDF of NPK (150:60:40 kg/ha) + Sulfur 40 kg/ha

T3: RDF of NPK (150:60:40 kg/ha) + Boron 3 kg/ha (15.65g borax) + Zinc 5 kg/ha

T4: RDF of NPK (150:60:40 kg/ha) + Boron 6 kg/ha + Zinc 10 kg/ha

T5: RDF of NPK (150:60:40 kg/ha) + Zinc 5 kg/ha + Sulfur 3.5 kg/ha + Boron 3 kg/ha

T6: RDF of NPK (150:60:40 kg/ha) + Zinc 10 kg/ha + Sulfur 7 kg/ha + Boron 7 kg/ha

Control: RDF of NPK (150:60:40 kg/ha)

Soil sampling and analysis

Before applying farmyard manure (FYM) and chemical fertilizers, soil samples were collected from each replication at a depth of 15 cm using a soil auger. The samples were pooled into a composite sample and analyzed at the Tarhara Soil Lab, Jhumka. Soil pH was measured with a pH meter (Kang *et al*., 2021), while available nitrogen (N), phosphorus (P), and potassium (K) were determined using standard procedures (Aryal *et al*., 2024). The soil at the research site was clay loam, with a pH of 6.2, nitrogen content of 0.21%, phosphorus content of 0.23%, and potassium content of 0.8%.

Field preparation and cultivation practices

The research field was prepared 10 days before sowing by removing crop residue, plowing to a depth of 5-6 cm, and dividing the area into experimental plots. Fertilizers were applied based on the recommended dose of 150:60:40 kg NPK/ha, with urea split and applied at 30 and 45 DAS. The TX-369 maize variety was sown in January 2023 at a rate of 25-30 kg/ha, with seeds placed 4-5 cm deep in furrows and spaced at 75 cm between rows and 25 cm between plants. Thinning and gap filling were conducted 20 days after sowing to retain one healthy seedling per hole. Irrigation was provided using a rose can immediately after sowing, followed by furrow irrigation based on field conditions. Weeding was done at 30 and 60 DAS, and earthing up occurred at 45 DAS. Chlorpyrifos and cypermethrin were applied at 45 and 75 DAS to manage pests, and handpicking of white grubs and cutworms was done as needed. Harvesting took place in June 2023 when the cobs were fully mature, and seeds were hard and dry.

Observed parameters

Vegetative parameters: Vegetative data were collected from eight randomly selected plants, excluding borderline plants, at 30, 45, 60, 75, 90, and 105 DAS. Plant height was measured from the base to the top leaf. The number of green leaves per plant was recorded by counting fully opened green leaves, excluding senescent or emerging leaves. Leaf area was calculated by measuring the length and width of healthy leaves.

Yield parameters: Yield parameters were assessed at harvest.

Ear height, ear length, and ear diameter were measured from eight tagged plants using measuring tools. Ear weight was recorded after husk removal, and kernel rows per ear and grains per row were counted. Test weight (1000-grain weight) was determined, and biological yield was calculated by measuring the total plant biomass. Grain yield was recorded after cobs were air-dried, shelled, and cleaned, while stover yield was determined by weighing the remaining plant material.

Data analysis

Data on vegetative and yield parameters were entered into Microsoft Excel (2016) and statistically analyzed using RStudio (v4.3.1). The analysis included ANOVA to determine treatment effects, with significance levels set at 5% and 1%. The least significant difference (LSD), grand mean, coefficient of variation (CV), mean square error (MS error), and standard error of the mean (SEM) were calculated for each parameter.

RESULTS AND DISCUSSION

Vegetative parameters

No significant differences were found in plant height, and number of leaves, across treatments at 30, 45, 60, 75, 95, and 105 DAS, but treatments significantly affected leaf area throughout the cropping period. Micronutrient application had no impact on plant height and leaves. These findings align with those of Tunebo *et al*. (2021), who noted that $ZnSO_4$ treatment did not affect plant height. Joshia *et al*. (2024) reported a similar result, exhibiting that the variance analysis demonstrates the non-significant variation in plant height under various B and Zn treatments.

Leaf area

Combined application of Zn, S, and B significantly affected leaf area. The highest leaf area i.e., 23.26, 50.15, 181.24, 404.52, 719.26, 750.95 cm2 at 30, 45, 60, 75, 90, and 105 DAS were obtained in T6 (RDF OF NPK+ zinc 10kg/ha+ Sulphur 7kg /ha {28.56g ZnSO4) + boron 6kg/ha). A similar outcome was reported by Jagasia *et al.* (2024), who found that the interaction between zinc and sulfur promotes chlorophyll synthesis and auxin metabolism, leading to increased leaf area production. This occurs due to their role in enhancing cell division and proliferation, which accelerates the growth of meristematic tissues. The resulting larger leaf area positively impacts photosynthesis by increasing the surface area available for light absorption. Boron also plays a critical role in transporting processed nutrients to actively developing regions, such as leaves, thereby prolonging the vegetative growth stage. Additionally, boron produces and enhances growth hormones that preserve chlorophyll content (Albayaty & Jumaa, 2024). The increase in leaf area can be attributed to elevated levels of tryptophan, an amino acid, and the indole acetic acid hormone, both of which are linked to leaf area expansion as influenced by the application of micronutrients (Adarsha *et al*., 2019). The integration of zinc with the recommended dose of NPK and other micronutrients benefits plant growth due to zinc's involvement in the synthesis of tryptophan and its role in producing various metabolic and storage compounds. These compounds contribute to cell growth, expansion, and the formation of new cells, thereby increasing the leaf area index (Huthily *et al*., 2020).

Yield parameter

Ear height, length, and diameter: The application of different micronutrients has no significant effect on the ear height of the corn. Results showed significant effects of micronutrients on ear length (Table 4). The highest ear length was obtained in T6 i.e., 19.56±0.32 cm followed by T3, T1, and control which were at par with each other. In contrast, the lowest ear length was obtained in T2. Applied micronutrients had significant effects on ear diameter (Table 4). The highest ear diameter was obtained in T6. i.e., 62.64±6.03 cm which was at par with control. Similarly, the lowest ear diameter was obtained in T5 i.e., 52.65 cm which was at par with T2 (55.30 cm). This finding is consistent with reports from Hisham *et al*. (2021), who noted that zinc application can enhance ear length and diameter by up to 20%. In addition, Maseeh and Dawson (2021), found that the rate of nitrogen and sulfur positively impacted physiological processes, plant metabolism, cob length, cob weight, etc.

Kernel row per ear: It is the most important parameter in the economic sector of production, the highest kernel row per year signifies the longer cob length and increased grain yield. Under the present study, the combined application of Zn, B, and S with RDF of NPK had a significant effect on KRPE (Table 4). The highest KRPE was observed in T6 i.e., 15.72±0.07 followed by T3, T1, and T2. Meanwhile, the lowest value was obtained in control i.e., 14.57 which was at par with T4, and T5. Higher zinc levels lead to a significantly greater number of kernel rows compared to the control. According to Hisham *et al.* (2021), who obtained that zinc application can escalate the number of kernel rows by 12%.

Grain per row: The present study signifies that the combined application of Zn, B, and S with RDF of NPK had a significant effect on grain per row (Table 4). The highest value was observed in T6 i.e., 44.25±0.34 followed by T1. Similarly, the lowest value was obtained in T4. This combination resulted in a significant increase in the number of rows per ear compared to both the control and the treatment with NPK applied alone. The application of micronutrients and their combinations to maize demonstrated beneficial effects on all physiological and yield parameters, including an increase in the number of grain rows per cob. Venkatesh (2023) and Riwad & Alag (2023) reported similar findings, indicating that the number of grain rows per cob in maize increases with the application of boron alongside macronutrients.

Table 1. Effect of micronutrients on plant height at different DAS in winter maize.

Treatment	Plant height at 30 DAS (cm)	Plant height at 45 DAS (cm)	Plant height at 60 DAS (cm)	Plant height at 75 DAS (cm)	Plant height at 90 DAS (cm)	Plant height at 105 DAS (cm)
T1	3.08^{a}±0.40	10.16^{a}±0.67	22.26^{a}±1.45	42.28^{a}±1.84	116.83^{a}±11.9	183.83^{a}±3.36
T2	3.26^{a}±0.46	9.38^{a}±0.80	23.08^{a}±3.52	44.33^{a}±5.43	112.62^{a}±17.8	177.00^{a}±8.45
T3	2.85^{a}±0.26	9.79^{a}±0.45	20.76^{a}±0.73	43.16^{a}±0.67	116.24^{a}±7.32	179.49^{a}±5.60
T4	3.02^{a}±0.55	9.89^{a}±0.63	19.85^{a}±3.26	39.00^{a}±5.64	110.70^{a}±21.9	177.41^{a}±8.92
T5	3.24^{a}±0.46	9.68^{a}±0.59	20.54^{a}±1.25	39.50^{a}±4.31	103.66^{a}±12.1	179.08^{a}±6.70
T6	3.13^{a}±0.08	9.77^{a}±0.62	23.55^{a}±3.48	48.20^{a}±3.92	120.91^{a}±13.8	167.08^{a}±21.6
Control	3.48^{a}±0.17	10.55^{a}±0.45	23.56^{a}±2.43	44.56^{a}±3.94	122.70^{a}±13.0	184.45^{a}±2.06
Grand mean	3.15	9.88	21.94	43.00	114.81	178.33
CV %	13.10	6.84	15.81	12.00	16.59	7.40
SEM	0.238	0.390	2.004	2.981	10.99	7.627
MS error	0.171	0.458	12.05	26.66	362.9	174.5
F value	0.697^{ns}	0.92^{ns}	0.59^{ns}	1.12^{ns}	0.34^{ns}	0.57^{ns}
LSD	0.709	1.160	5.95	8.85	32.67	22.66

^{ns} = non-significant, same letter signifies no significant difference between treatments (homogeneity effects of treatments).

Table 2. Effect of micronutrient on number of leaves at different DAS in winter maize.

Treatment	No. of leaves at 30 DAS	No. of leaves at 45 DAS	No. of leaves at 60 DAS	No. of leaves at 75 DAS	No. of leaves at 90 DAS	No. of leaves at 105 DAS
T1	3.95^{a}±0.15	5.37^{a}±0.14	7.08^{a}±0.34	9.33^{a}±0.35	10.16^{a}±0.43	10.75^{a}±0.38
T2	3.91^{a}±0.04	5.04^{a}±0.27	7.21^{a}±0.39	9.20^{a}±0.70	9.91^{a}±0.47	10.16^{a}±0.34
T3	3.87^{a}±0.14	4.62^{a}±0.19	7.25^{a}±0.28	9.12^{a}±0.21	10.12^{a}±0.32	13.91^{a}±3.73
T4	4.00^{a}±0.14	5.16^{a}±0.41	6.58^{a}±0.37	8.37^{a}±0.83	9.33^{a}±0.80	9.91^{a}±0.68
T5	3.91^{a}±0.16	4.95^{a}±0.44	6.79^{a}±0.27	8.66^{a}±0.29	9.83^{a}±0.44	10.54^{a}±0.29
T6	3.87^{a}±0.14	5.20^{a}±0.15	7.37^{a}±0.38	9.29^{a}±0.55	10.29^{a}±0.69	10.83^{a}±0.40
Control	3.95^{a}±0.08	5.20^{a}±0.18	7.49^{a}±0.19	9.46^{a}±0.29	10.29^{a}±0.34	10.74^{a}±0.33
Grand mean	3.92	5.08	7.11	9.06	9.99	10.98
CV %	4.10	10.17	6.55	7.74	6.75	21.55
SEM	0.094	0.298	0.269	0.405	0.389	1.366
MS error	0.026	0.267	0.217	0.493	0.455	5.60
F value	0.25^{ns}	0.65^{ns}	1.44^{ns}	0.94^{ns}	0.75^{ns}	0.95^{ns}
LSD	0.276	0.886	0.799	1.204	1.157	4.05

^{ns} =non-significant, same letter signifies no significant difference between treatments (homogeneity effects of treatments).

Table 3. Effect of micronutrients on leaf area at different DAS in maize.

Treatment	Leaf area at 30 DAS	Leaf area at 45 DAS	Leaf area at 60 DAS	Leaf area at 75 DAS	Leaf area at 90 DAS	Leaf area at 105 DAS
T1	20.83^{ab}±0.91	42.12^{a}±0.41	115.02^{a}±12.2	298.93^{a}±17.2	621.26^{a}±16.8	625.00^{a}±15.1
T2	20.46^{ab}±0.84	38.68^{a}±4.20	128.430^{ab}±35.7	330.71^{ab}±52.1	595.64^{a}±59.2	593.00^{a}±66.7
T3	18.08^{a}±1.08	38.45^{a}±2.38	100.86^{a}±4.82	282.15^{a}±9.66	601.62^{a}±6.87	597.37^{a}±12.1
T4	17.25^{a}±1.42	38.98^{a}±3.32	93.90^{a}±17.2	244.54^{a}±53.5	564.43^{a}±36.5	584.87^{a}±40.1
T5	18.62^{a}±1.98	37.14^{a}±0.60	93.13^{a}±12.8	252.07^{a}±53.3	559.37^{a}±29.0	592.22^{a}±31.6
T6	23.26^{b}±0.26	50.15^{b}±0.97	181.24^{b}±16.5	404.52^{b}±23.1	719.26^{b}±34.4	750.95^{b}±21.3
Control	20.37^{ab}±0.35	40.55^{a}±3.92	123.16^{a}±25.4	314.67^{ab}±33.5	573.14^{a}±34.4	566.32^{a}±6.27
Grand mean	19.84	40.87	119.39	303.94	604.96	615.67
CV %	9.007	10.60	25.17	9.88	8.79	9.36
SEM	1.079	2.502	17.353	31.04	30.704	33.274
MS error	6.312	18.78	903.4	2891	2828	3322
F value	3.52*	3.08*	3.11*	3.05*	3.21*	3.48*
LSD	3.06	7.43	51.55	51.55	91.22	98.86

(*) = significant at 5%, same letter signifies no significant difference between treatments (homogeneity effects of treatments).

Table 4. Effect of micronutrients on different parameters in winter maize.

Treatment	Ear height	Ear length	Ear diameter	Kernel row per ear	Grain per row	Ear weight (ton/ha)
T1	53.37^{a}±1.45	18.54^{ab}±0.23	57.94^{ab}±6.36	15.21^{ab}±0.15	38.04^{bc}±0.73	15.31^{b}±0.87
T2	48.43^{a}±5.38	17.77^{a}±0.32	55.30^{a}±5.01	15.16^{ab}±0.41	34.29^{ab}±1.34	13.21^{a}±3.83
T3	55.85^{a}±4.02	18.89^{ab}±0.13	56.88^{ab}±4.40	15.37^{ab}±0.45	36.88^{abc}±1.15	15.57^{b}±3.40
T4	50.98^{a}±5.29	18.12^{a}±0.55	57.59^{ab}±4.68	14.58^{a}±0.33	28.83^{a}±7.23	13.64^{ab}±1.72
T5	50.77^{a}±6.25	18.08^{a}±0.62	52.65^{a}±4.11	14.62^{a}±0.12	35.25^{ab}±2.03	14.15^{ab}±5.95
T6	58.44^{a}±2.10	19.56^{b}±0.32	62.64^{b}±6.03	15.72^{b}±0.07	44.25^{c}±0.34	17.65^{c}±0.43
Control	58.08^{a}±2.87	18.75^{ab}±0.16	61.75^{b}±4.89	14.57^{a}±0.25	37.58^{abc}±0.37	14.42^{ab}±0.27
Grand mean	53.70	18.53	57.82	15.06	36.44	14.85
CV%	11.17	3.21	5.24	3.25	12.68	7.009
SEM	3.468	0.344	1.752	0.282	2.669	0.600
MS error	36.01	0.355	9.2	0.24	21.37	1.083
F value	1.25^{ns}	3.07*	3.94*	3.31*	3.01*	6.17**
LSD	10.29	1.02	5.20	0.840	7.92	1.785

^{ns} = non-significant, (*) = significant at 5 %, (**) = significant at 1%, same letter signifies no significant difference between treatments (homogeneity effects of treatments).

Table 5. Effect of micronutrient on different parameters in winter maize.

Treatment	Biological yield (ton/ha)	Test weight	Grain yield (ton/ha)	Stover yield (ton/ha)
T1	28.52^{ab}±1.82	413.33^{bc}±6.67	11.32^{ab}±0.38	3.29^{ab}±0.24
T2	22.93^{a}±2.22	438.33^{c}±4.41	9.53^{a}±0.93	2.81^{a}±0.19
T3	28.40^{ab}±1.89	406.66^{abc}±6.67	10.71^{a}±0.66	3.38^{c}±0.09
T4	24.23^{a}±4.07	373.33^{ab}±6.67	10.11^{a}±0.73	2.84^{ab}±0.19
T5	24.28^{a}±2.82	360.00^{a}±20	10.56^{a}±0.48	2.90^{ab}±0.16
T6	34.80^{b}±2.49	393.33^{abc}±13.3	12.68^{b}±0.28	3.39^{bc}±0.10
Control	25.41^{a}±0.80	373.33^{ab}±26.7	10.41^{a}±0.43	2.96^{abc}±0.09
Grand mean	26.92	394.04	10.76	3.08
CV%	14.21	6.64	8.88	8
MS error	14.65	686.1	0.915	0.0608
SEM	2.209	15.123	0.552	0.142
F value	3.38*	3.28*	3.32*	3.26*
LSD	6.56	44.93	1.64	0.422

(*) = significant at 5 %, same letter signifies no significant difference between treatments (homogeneity effects of treatments)

Ear weight: A significant effect of secondary and micronutrients was observed (T6). Combined application of Zn, B, and S with RDF OF NPK (T6) gives the highest ear weight i.e., 17.65 ±0.43ton/ha followed by T3 (15.57 ton/ha) and T1 (15.31 ton/ha). similarly, the lowest ear weight was obtained when applying S with RDF of NPK i.e., in T2 (13.21 ton/ha). The application of zinc via foliar or soil increases the ear weight. A similar outcome was reported by Berhe and Marie (2020), who indicated that the use of blended fertilizers could enhance grain weight, due to beneficial interactions between macronutrients and micronutrients.

Biological yield: In the study, applied micronutrients showed a significant effect on the biological yield of maize (Table 5). Combine application of Zn, B, and S with RDF of NPK signifies the highest biological yield i.e., 34.80±2.49 ton/ha in T6 followed by T1 (28.52 ton/ha) and T3 (28.40 ton/ha). The lowest biological yield was obtained in T2 (22.93 ton/ha) which was at par with T5 (24.28 ton/ha), T4 (24.23 ton/ha), and control (25.41 ton/ha). The increase in leaf area, chlorophyll levels, and grain production may contribute to the rise in biological yield. This effect can be attributed to the application of micronutrients, which activate various physiological processes, including stomatal regulation, chlorophyll synthesis, enzyme activation, and other biochemical functions (Younis *et al*., 2020). Zinc has a vital role in regulating the concentration of auxin that increases the majority of plant's physiological and metabolic activities, which helps plants absorb more nutrients from the soil, resulting in higher plant growth (Mian *et al*., 2021). Zinc accelerates the photosynthesis process, and the movement of photo assimilates, contributes to producing more biological yield (Shaaban *et al*., 2023). B and Zn fertilizers applied in soil either sole or combined slightly enhanced biomass, but significantly increased total B and Zn plant uptake with significant differences between soil types (Shrestha *et al*., 2021).

Test weight: Applied Sulphur with RDF of NPK had a positive effect on 1000 grain weight of maize. When applied Sulphur 40kg/ha with RDF of NPK provided the highest 1000 grain weight (Test weight) i.e., 438.33±4.41 gm followed by T1 (413.33 gm) which was at par with T1, T3, and T6. Similar findings were reported by Praveena & Singh (2020), who noted that sulfur application enhances maize test weight because it facilitates the synthesis of amino acids like cysteine, cystine, and methionine through enzymatic processes. El-Azeiz & Hamdy (2023), demonstrated that since sulfur is a necessary nutrient for plant growth, increasing the amount of elemental sulfur fertilizers produced the highest vegetative growth values when compared to the control. The application of S fertilizer significantly influenced 100-grain weight and grain moisture content (Jiang *et al*., 2024).

Grain and stover yield: The combined application of sulphur, zinc, and boron with the recommended dose of fertilizer (RDF) of NPK significantly influenced grain and stover yields (Table 5). The highest grain yield was recorded in T6 (12.68 ± 0.28 ton/ha), followed by T1 (11.32 ton/ha), while the lowest was observed in T2 (9.53 ton/ha), which was statistically at par with T3, T4, T5, and the control. Similarly, the application of micronutrients had a significant effect on stover yield. The highest stover yield was achieved with the combined application of Zinc, Boron, and Sulphur along with RDF of NPK in T6 (3.39 ton/ha), followed closely by T3 (3.38 ton/ha), whereas the lowest stover yield was observed in T2 (2.81 ton/ha). Saboor *et al*. (2021) concluded that applying zinc at 20 kg/ha is an effective treatment for achieving better growth and higher maize yields by enhancing photosynthesis, transpiration, and stomatal conductance without causing zinc deficiency or toxicity. Similarly, Rawat *et al*. (2021) observed that the highest grain and stover yields were achieved with the application of 100% of the recommended dose of NPK along with sulfur and zinc. Sulfur plays a vital role in improving maize growth characteristics, yield quality and overall productivity. Its availability significantly influences the uptake of primary nutrients and the efficiency of fertilizers (Ariraman *et al*., 2020). Additionally, zinc maintains cellular membrane integrity, facilitates protein and auxin synthesis, and activates plant enzymes involved in glucose metabolism, all of which are crucial for plant development and result in higher grain yields (Abednego *et al*., 2023). The combined application of zinc, boron, sulfur, and macronutrients also significantly enhances drought stress tolerance by detoxifying reactive oxygen species (ROS) and boosting the activity of antioxidant enzymes (Shemi *et al*., 2021). Furthermore, zinc improves germination rates, product quality, and agricultural productivity per unit area (Lamlom *et al*., 2024).

Conclusion

Applying zinc, boron, and sulfur alongside the recommended NPK dose significantly enhanced maize growth and yield parameters, excluding vegetative traits. The treatment combining 10 kg/ha of Zn, 6 kg/ha of B, and 7 kg/ha of S with NPK (Zn10 + B6 + S7 kg/ha + RDF of NPK) produced the highest ear diameter, ear weight, biological yield, and grain yield. Meanwhile, the highest test weight was observed with the application of 40 kg/ha of S and NPK (S40 kg/ha + RDF of NPK). These results suggest that the optimal combination of micronutrients with NPK not only maximizes maize production but also supports soil health in the local environment.

DECLARATIONS

Authors contribution statement

Conceptualization: A.T. and D.A.; Methodology: R.M.; Software and validation: A.T., P.C., and D.A.; Formal analysis and investigation: A.T.; Resources: D.A.; Data curation: R.M.; Writing—original draft preparation: A.T.; Writing—review and editing: A.T.; Visualization: R.T.; Supervision: D.A.; Project administration: R.M.; Funding acquisition: R.T. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest: The authors state that there are no conflicts of interest concerning the publication of this manuscript.

Ethics approval: This study did not include any animal or human participants, so ethical approval was not required.

Consent for publication: All co-authors provided permission to publish this paper in AAES.

Data availability: The data that support the findings of this study are available on request from the corresponding author.

Supplementary data: Not available.

Funding: No financial support was received for this study.

ACKNOWLEDGMENT

We extend our heartfelt gratitude to our parents for their unwavering support. We also thank the Institute of Agriculture and Animal Science (IAAS), Tribhuvan University, for the valuable research opportunities through the Undergraduate Practicum Assessment (UPA). Special thanks to Gauradaha Agriculture Campus for the guidance from professors and the support from lab members throughout our research.

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